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(54) Title: HETEROLOGOUS ANTIGENS IN LIVE CELL VACCINE STRAINS		
(57) Abstract A bacterial cell (preferably a gram-negative, enteric bacterium such as <i>V. cholerae</i> ) the chromosome of which contains a DNA sequence encoding a heterologous antigen, which sequence is functionally linked to an iron-regulated promoter such as the <i>hlyA</i> promoter of <i>V. cholerae</i> .		

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**HETEROLOGOUS ANTIGENS IN LIVE CELL VACCINE STRAINS**

The field of the invention is genetically engineered live bacterial cell vaccine strains.

**Statement as to Federally Sponsored Research**

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**Background of the Invention**

*V. cholerae* is a gram-negative bacterium that causes a severe, dehydrating and occasionally fatal diarrhea in humans. There are an estimated 5.5 million cases of cholera each year, resulting in greater than 100,000 deaths (Bull. W.H.O. 68:303-312, 1990). Over the last several decades, cholera has been considered to occur primarily in developing countries of Asia and Africa, but recently it has reached epidemic proportions in regions of South and Central America, as well (Tauxe et al., J. Am. Med. Assn. 267:1388-1390, 1992; Sverdlov et al., J. Am. Med. Assn. 267:1495-1499, 1992). Patients who recover from cholera infection have long-lasting, perhaps lifelong, immunity to reinfection (Levine et al., J. Infect. Dis. 143:818-820, 1981). The development of *V. cholerae* vaccines has focused on reproducing this naturally occurring immunity, but the currently available parenteral, killed whole-cell vaccine preparation provides less than 50% protection from disease, for a duration of only 3 to 6 months (Saroso et al., Bull. W.H.O. 56:619-627, 1978; Levine et al., Microbiol. Rev. 47:510-550, 1983). A genetically-engineered, live oral vaccine for *V. cholerae* has several theoretical advantages over the present parenteral killed whole-cell vaccine. As a mucosal pathogen, *V. cholerae*

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adheres selectively to the M cells of the gastrointestinal tract (Owen et al., J. Infect. Dis. 153:1108-1118, 1986) and is a strong stimulus to the common mucosal immune system (Svennerholm et al., Lancet i:305-308, 1982); and oral cholera vaccination in humans produces a strong salivary gland IgA response to cholera toxin B subunit (Czerkinsky et al., Infect. Immun. 59:996-1001, 1991). Oral vaccines take advantage of the fact that oral administration of antigens appears to be the most efficient stimulus for the development of secretory IgA (Svennerholm, *supra*), and that secretory IgA by itself is sufficient to protect against intestinal disease from *V. cholerae* (Winner III, et al., Infect. Immun. 59:977-982, 1991). Oral, killed whole cell vaccines with or without the B subunit of cholera toxin have undergone extensive testing in volunteer and field trials over the past decade, and have been found to be more immunogenic and confer longer protection than the parenteral killed whole-cell vaccine (Svennerholm et al., J. Infect. Dis. 149:884-893, 1984; Black et al., Infect. Immun. 55:1116-1120, 1987; Clemens et al., Lancet i:1375-1378, 1988; Clemens et al., J. Infect. Dis. 158:60-69, 1988; Jertborn et al., J. Infect. Dis. 157:374-377, 1988; Sack et al., 164:407-11, 1991). Such killed whole-cell vaccines were traditionally favored over live whole-cell vaccines because the latter, which can multiply in the gut of the vaccinated animal, were considered unsafe. However, unlike killed-cell vaccines, live-cell vaccines would not require multiple doses, and in a rabbit model, live bacteria are more effective immunogens for secretory IgA than dead organisms (Keren et al., J. Immunol. 128:475-479, 1982). Live vaccines have the further advantage of potentially being transmitted from recipients to others in the community, leading to herd immunity.

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The most important virulence factor for *V. cholerae* in causing clinical disease is cholera toxin, a protein complex consisting of one A subunit and 5 B subunits. Live, oral vaccine strains currently being tested bear mutations in either the A subunit or in both subunits of cholera toxin (Mekalanos et al., Nature 306:551-557, 1983; Harrington et al., J. Exp. Med. 168:1487-1492, 1988; Levine et al., Lancet ii:467-470, 1988). An internal deletion of the gene encoding the A subunit of cholera toxin (ctxA) in the classical strain 0395 produces a strain (0395-N1) which is highly immunogenic in humans, but produces non-specific symptoms in about half of the recipients (Mekalanos, supra; Harrington, supra; Mekalanos, U.S. Patent No. 4,882,278, herein incorporated by reference), an indication that the strain is still virulent.

#### Summary of the Invention

As described in detail below, it has now been found that a *V. cholerae* gene, such as the *iryA* locus of *V. cholerae*, can function as a site for the integration and high-level expression of sequences encoding heterologous antigens in vaccine strains of *V. cholerae*. *IryA*, the major iron-regulated outer membrane protein of *V. cholerae*, is a virulence factor for this organism that is independent of cholera toxin (Goldberg et al., USSN 07/629,102, herein incorporated by reference; Goldberg et al., Infect. Immun. 58:55-60, 1990). In vivo-grown *V. cholerae* expresses iron-regulated proteins that are not seen following growth in normal in vitro conditions (Sciortino et al., 42:990-996, 1983), suggesting that the organisms sense low-iron conditions in the intestine. A mutation in *iryA* produces a 100-fold defect in the virulence of *V. cholerae* in a suckling mouse model. Regulation of *iryA* expression by iron is

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exceptionally tight, with a 1000-fold induction ratio in low- compared with high-iron conditions (Goldberg et al., Infect. Immun. 58:55-60, 1990). The entire structural gene of *iryA* has been cloned from the classical *V. cholerae* strain 0395 (Goldberg et al., Mol. Microbiol. 6:2407-2418, 1992). Use of such an iron-regulated promoter to control expression of a heterologous antigen in a live vaccine strain has a number of distinct advantages. A high induction ratio ensures that the gene encoding the heterologous antigen (1) will be expressed in the low-iron environment of the vaccinee's gut at a level high enough to ensure that it induces an immune response, and yet (2) will be expressed minimally when the cells are cultured in vitro, where high-level expression would potentially provide selection pressure favoring inactivation of the gene and complicate large-scale culturing of the cells necessary for vaccine production. Where, as in the case of *iryA*, the protein encoded by the naturally-occurring gene is, for at least some *V. cholerae* strains, a virulence factor that is not essential for growth of the bacterium, insertion of the heterologous antigen coding sequence next to the promoter can be readily accomplished in such a way as to delete or otherwise inactivate the virulence factor coding sequence, thereby decreasing the virulence of the engineered strain without affecting its viability.

The invention thus includes a genetically engineered *V. cholerae* chromosome containing a DNA sequence encoding a heterologous antigen, the DNA sequence being functionally linked to a naturally-occurring *V. cholerae* promoter. The heterologous antigen, defined as a polypeptide which is not expressed by the wildtype host species, is preferably a nontoxic polypeptide which is part or all of a protein that is naturally expressed by an infectious organism, and which

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induces an antigenic response in an animal (preferably a mammal such as a human, non-human primate, cow, horse, sheep, goat, pig, dog, cat, rabbit, rat, mouse, guinea pig, or hamster). The infectious organism from which the heterologous antigen is derived may be, for example, a bacterium, a virus, or a eukaryotic parasite, and the heterologous antigen may be, e.g., an OSP (Outer Surface Protein) of *Borrelia burgdorferi*; an immunogenic, nontoxic subunit or fragment of a bacterial toxin such as Shiga toxin, diphtheria toxin, *Pseudomonas* exotoxin A, pertussis toxin, tetanus toxin, anthrax toxin, one of the *E. coli* heat-labile toxins (LTs), one of the *E. coli* heat-stable toxins (STs), or one of the *E. coli* Shiga-like toxins; an immunogenic portion of a viral capsid from a virus such as human immunodeficiency virus (HIV), any of the Herpes viruses (e.g., Herpes simplex virus or Epstein-Barr virus), influenza virus, poliomyelitis virus, measles virus, mumps virus, or rubella virus; or an immunogenic polypeptide derived from a eukaryotic parasite, such as the causative agent for malaria, pneumocystis pneumonia, or toxoplasmosis. (One preferred example of such a polypeptide is a malarial circumsporozoite protein.) By "functionally linked to a naturally-occurring *V. cholerae* promoter" is meant that expression of the sequence encoding the heterologous antigen is controlled by a promoter which is found in wild-type *V. cholerae*, such as the *ctxA* promoter, or an iron-regulated promoter such as that of *irgA*. Construction of such a functional linkage can be accomplished as described in detail below, or generally, using standard methods, by locating the desired promoter sequence sufficiently near to (and typically, though not necessarily, just upstream of) the promoterless heterologous antigen-encoding sequence to permit the desired promoter sequence to control expression of the

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latter sequence. Functional siting of promoter sequences is well within the abilities of one of ordinary skill in the art of prokaryotic gene expression. Where the promoter naturally controls the expression of a *V. cholerae* virulence factor that is nonessential for growth of the cell, the sequence encoding that virulence factor will preferably be deleted or otherwise mutated to prevent expression of a biologically active form of that virulence factor. Preferably, the *ctxA* locus on the chromosome will also be deleted or otherwise inactivated, so that biologically active cholera toxin cannot be expressed from the chromosome. Such deletions, mutations and insertions can readily be carried out by one of ordinary skill using the methods described herein, or other well-known, standard techniques. In preferred embodiments, the *ctxA* deletion is identical to that of strain 0395-N1 (Mekalanos, U.S. Patent No. 4,882,278).

Also within the invention is a bacterial chromosome (preferably from a gram-negative, enteric bacterium such as *V. cholerae*), containing a DNA sequence encoding a heterologous antigen, which sequence is functionally linked to an iron-regulated promoter which functions in the host bacterium to permit significantly (i.e., at least ten-fold and preferably 100-fold) higher expression of the heterologous antigen in a low-iron environment, such as in an animal's intestine, than in a high-iron environment, such as under typical *in vitro* culture conditions. An example of such a promoter is the naturally-occurring promoter of *V. cholerae irgA*, which includes at a minimum a sequence substantially identical to nucleotides 1000 through 1041 (SEQ ID NO: 2), inclusive, of the sequence shown in Fig. 5 (SEQ ID NO: 1). The promoter sequence used is preferably nucleotides 922 to 1041 (SEQ ID NO: 3), more preferably 922 to 1079 (SEQ ID NO: 4) or 1000 to 1079 (SEQ ID

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NO: 5), still more preferably 905 to 1041 (SEQ ID NO: 6) or 905 to 1079 (SEQ ID NO: 7), and most preferably 905 to 1438 (SEQ ID NO: 8), 922 to 1438 (SEQ ID NO: 9), or 1000 to 1438 (SEQ ID NO: 10) (all inclusive). Examples of other iron-regulated promoters which would be useful in the invention are those derived from the *fatA* gene of *V. anguillarum* (Koster et al. J. Biol. Chem. 266:23829-23833, 1991); *E. coli* *slt-1A* (or other *E. coli* Fur-binding promoter sequences, as discussed by Calderwood et al., J. Bacteriol. 169:4759-4764, 1987; De Grandis et al., J. Bacteriol. 169:4313-4319, 1987; and DeLorenzo et al., J. Bacteriol. 169:2624-2630, 1987); the iron-regulated outer membrane proteins of *Salmonella typhi* (Fernandez et al., Infect. Immun. 57:1271-1275, 1989), the iron-regulated hemolysin promoter of *Serratia* (Poole et al., Infect. Immun. 56:2967-2971, 1988); the *Yersenia* iron-regulated promoters (Carniel et al., Molecular Microbiol. 6:379-388, 1992; Staggs et al., J. Bacteriol. 173:417-425, 1991; and Staggs et al., Molecular Microbiol. 6:2507-2516, 1992); the *V. vulnificus* iron-regulated promoters; the *Pseudomonas* exotoxin A iron-regulated promoter (Bjorn et al., Infect. Immun. 19:785-791, 1978); and *Plesiomonas* iron-regulated genes involved in heme-iron uptake (Daskaleros et al., Infect. Immun. 59:2706-2711, 1991). It is believed that most if not all enteric, gram-negative bacterial species, including *E. coli*, *Salmonella*, *Shigella*, *Yersenia*, *Citrobacter*, *Enterobacter*, *Klebsiella*, *Moryanella*, *Proteus*, *Providencia*, *Serratia*, *Vibrio*, *Plesiomonas*, and *Aeromonas*, utilize highly similar fur-binding, iron-regulated promoter sequences, and it is likely that they also utilize secondary iron-regulated promoter sequences similar to that of *iryA*. Such promoter sequences are well-known to those of ordinary skill, or can be readily determined from current information regarding iron-

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regulated promoters. Construction of such promoter sequences adjacent to a given heterologous antigen-encoding sequence, and insertion of the resulting construct into a *V. cholerae* genome, is readily accomplished by one of ordinary skill; the ability of such a promoter to function as predicted can then be tested in low- and high-iron conditions as described below, without undue experimentation.

Also within the invention is a *V. cholerae* cell, or a homogeneous population of such cells, which contains the genetically engineered chromosome described above. Such cells can be said to define a vaccine strain useful, when combined with a pharmaceutically acceptable diluent suitable for oral administration, as a live-cell vaccine. Administration of such a vaccine to an animal (e.g., a human or other mammal) will provoke immunity not only to *V. cholerae*, but also to an antigen derived from a second organism; it thus serves as a bivalent vaccine. An example of such a vaccine utilizes a genetically engineered *V. cholerae* strain in which the *ctxA* and *iryA* coding sequences are largely deleted and a sequence encoding Shiga-like toxin B subunit is functionally linked to the *iryA* promoter. This strain is described in detail below. Of course, the bacterial strain of the invention could be engineered to encode several heterologous antigens, each linked to an identical or different iron-regulated promoter, to produce a multivalent vaccine effective for simultaneously inducing immunity against a number of infectious diseases. Other features and advantages will be apparent from the detailed description provided below, and from the claims.

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**Brief Description of the Drawings**

Fig. 1 is a schematic diagram illustrating the construction of plasmids used in this study. A partial restriction map of 0395 chromosomal DNA is shown with 5 relevant restriction enzyme sites, using base-pair numbering as in Goldberg et al., Mol. Microbiol. 6:2407-2418, 1992; and Goldberg et al., Proc. Natl. Acad. Sci. USA 88:1125-1129, 1991. The location of *iryA*, the location of fragments cloned in the construction of 10 vaccine strains and the locations of fragments used as probes in Southern blot analysis are indicated. The upstream *iryA* fragment is indicated by a solid bar; the downstream *iryA* fragment by a hatched bar; and the *slt-IB* subunit fragment by a stippled bar. Plasmids and 15 chromosomal fragments are not drawn to scale.

Figs. 2A-2B is a set of Southern blots illustrating hybridization of chromosomal DNA from wild-type and mutant *V. cholerae* strains, digested with *HindIII*, separated by agarose electrophoresis and probed 20 as follows: (A) *SmaI* - *HincII* fragment (region deleted in vaccine strains); (B) *HincII* - *HincII* fragment (downstream probe); (C) *HindIII* - *SmaI* fragment (upstream probe); (D) *EcoRV* - *HindIII* fragment from pSBC52 (*slt-IB* subunit probe). Lanes: 1, 0395-N1; 2, SBC20; 3, B014-1; 25 4, B024-1; 5, VAC1; 6, VAC2; 7, 0395-N1. The genomic location of the fragments used as probes is indicated in Fig. 1. The numbers to the left of the blot indicate the sizes (in kbp) of DNA standards.

Fig. 3 is a photograph of an SDS-PAGE analysis of 30 the outer membrane proteins expressed by certain *V. cholerae* strains when grown in high- or low-iron medium. Lanes: 1, 0395-N1 grown in high-iron medium; 2, 0395-N1 grown in low-iron medium; 3, SBC20 grown in low-iron medium; 4, VAC1 grown in low-iron medium; 5, VAC2 grown 35 in low-iron medium; 6, 0395-N1 grown in low-iron medium.

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The numbers to the left of the gel indicate the molecular masses (in kDa) of the protein standards.

Fig. 4 is a schematic diagram of the construction of the pSBC52 plasmid utilized in these experiments.

5 pSBC32 (Calderwood et al., Infect. Immun. 58:2977-2982, 1990) was subjected to PCR using primer No. 1: 5'-CGAATTCTCTAGAGATATCGTGTGGAATTGTGACGGATAA-3' (SEQ ID NO: 11), which introduces restriction sites for *EcoRI*, *XbaI*, and *EcoRV*, and primer No. 2: 10 5'-CCAAGCTTCTGCGAGCCCGGATTACATTATGAATCTCCGCT-3' (SEQ ID NO: 12), which introduces restriction sites for *HindIII*, *PstI*, and *SmaI*. The PCR product was then digested with *EcoRI* and *HindIII*, and cloned into *EcoRI/HindIII*-digested pUC19, to produce pSBC52.

15 Fig. 5 shows the nucleotide sequence of a portion of the *iryA* cDNA (SEQ ID NO: 1), including the promoter sequence. A 19-bp interrupted dyad symmetric element homologous to the Fur box of *E. coli* is indicated by inverted horizontal arrows below the sequence. Vertical 20 lines mark the margins of what is believed to be regions important for *iryA* promoter function.

**Detailed Description**

In the experiments described below, the non-toxic B subunit of Shiga toxin was used as a model heterologous 25 antigen, because of the easily available assays for this protein (Donohue-Rolfe et al., J. Clin. Microbiol. 24:65-68, 1986), as well as the possible role that antibodies against the B subunit play in protecting against severe Shigellosis and hemolytic uremic syndrome. Shiga toxin 30 is a heterodimeric protein consisting of one A subunit (MW 32 kDa) and five B subunits (MW 7.7 kDa) (Seidah et al., J. Biol. Chem. 261:13928-13931, 1986); the B subunit of Shiga toxin is identical in amino acid sequence to the B subunit of Shiga-like toxin I produced by

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enterohemorrhagic strains of *E. coli* (Caldarwood et al., Proc. Natl. Acad. Sci. USA 84:4364-4368, 1987). This identical protein product is referred to as StxB throughout this study. Immune response to Shiga toxin is primarily directed against the B subunit, and antibodies directed against this subunit, or against synthetic peptides from regions of the subunit, provide protective immunity against holotoxin (Donohue-Rolfe et al., J. Exp. Med. 160:1767-1781, 1984; Harari et al. Infect. Immun. 56:1618-1624, 1988; Harari et al., Mol. Immunol. 27:613-621, 1990; Boyd et al., Infect. Immun. 59:750-757, 1991).

Described below are the insertion of a promoterless gene for the Shiga-like toxin I B subunit (*slt-IB*) into an *iryA* deletion, and the introduction of this construct into the chromosome of the *V. cholerae* *ctxA* deletion strain 0395-N1, thus producing a live, attenuated vaccine strain of *V. cholerae* that contains StxB under the transcriptional control of the iron-regulated *iryA* promoter.

## 20 MATERIALS AND METHODS

### Bacterial strains and plasmids.

The bacterial strains and plasmids used in this study are described in Table 1, with the exception of plasmids PMBG126, pSAB18, pSAB12, pSAB19, pSAB14, and pSAB24, which are described in detail below and are depicted in Fig. 1; and plasmid pSBCS2, which is described in the description of Fig. 4 provided above. Standard plasmid cloning vectors pUC18, pUC19, and pBR322 are commercially available (e.g., Pharmacia).

### 30 Media.

All strains were maintained at -70°C in Luria broth (LB) media (Sambrook et al., A Laboratory Manual, 2nd ed. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY, 1989), containing 1% glycerol. LB media,

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with or without the addition of the iron chelator 2,2-dipyridyl (final concentration, 0.2 mM), was used for growth in low- and high-iron conditions, respectively. Ampicillin (100 µg/ml), kanamycin (45 µg/ml), and streptomycin (100 µg/ml) were added as appropriate.

### Genetic methods.

Isolation of plasmid and bacterial chromosomal DNA, restriction enzyme digests, agarose gel electrophoresis, and Southern hybridization of DNA separated by electrophoresis were performed according to standard molecular biologic techniques (Sambrook, *supra*). GeneScreen Plus hybridization transfer membranes (DuPont Biotechnology Systems, NEN Research Products, Boston, MA) were used according to the manufacturer's protocols for Southern hybridization. DNA sequencing was performed using the Sequenase DNA Sequencing Kit (United States Biochemical Corporation, Cleveland, OH).

Plasmids were transformed into *E. coli* strains by standard techniques, or were electroplated into *V. cholerae* using a Gene Pulser (Bio-Rad Laboratories, Richmond, CA), following the manufacturer's protocol, and modified for electroporation into *V. cholerae* as previously described (Goldberg et al., Proc. Natl. Acad. Sci. USA 88:1125-1129, 1991). Electroporation conditions were 2,500 V at 25-µF capacitance, producing time constants of 4.7-4.9 ms.

DNA restriction endonucleases, *T<sub>4</sub>* DNA ligase, calf intestinal alkaline phosphatase, and the Klenow fragment of DNA polymerase I were used according to the manufacturers' specifications. Restriction enzyme-digested chromosomal and plasmid DNA fragments were separated on 1% agarose gels; required fragments were cut from the gel under ultraviolet illumination and purified by electroelution (Sambrook et al, 1989, *supra*). DNA fragments used as probes were radiolabeled with α-<sup>32</sup>P-dCTP

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using a random priming labeling kit (Prime Time "C" Oligonucleotide Labeling Biosystem, International Biotechnologies, Inc., New Haven, CT).

#### Construction of plasmids.

5 DNA was recovered upstream and at the 5' terminus of *iryA* as a *HindIII*-*SmaI* fragment from pMBG59, which contains the *iryA* promoter (*iryP*) (Goldberg et al., J. Bacteriol. 172:6863-6870, 1990) (Fig. 1). This fragment was cloned into the *HindIII* and *SphI* sites of pUC18 to yield plasmid pMBG126; the *SphI* site of pUC18 had first been made blunt-ended by treatment with mung bean nuclease. DNA sequence analysis of pMBG126 revealed that the *SphI* site was unexpectedly preserved at the junction with *SmaI*; the sequence was otherwise as predicted. DNA was then recovered at the 3' terminus and downstream of *iryA* as a 1.5 kilobase-pair (kbp) *HincII* fragment from plasmid pSAB25. *SacI* linkers were added to this fragment and it was ligated into the unique *SacI* site of pMBG126, in the same orientation as the upstream *iryA* fragment, to yield plasmid pSAB18. The internal *SalI* site in the pUC polylinker of pSAB18 was removed by digesting with *SalI*, treating with the Klenow fragment of DNA polymerase I, and religating the blunt ends, to create pSAB12. A DNA segment encoding the promoterless B subunit of Shiga-like toxin I (*slt-IB*) was recovered as an *EcoRV*-*SmaI* fragment from plasmid pSBC52. This fragment was introduced into the unique *EcoRV* and *SmaI* sites of pSAB18, such that *slt-IB* was under the transcriptional control of *iryP* on the upstream *iryA* fragment, yielding plasmid pSAB19. The construction of plasmids pMBG126, pSAB18, pSAB12, and pSAB19 was verified by restriction enzyme digestion and double-stranded DNA sequencing.

The desired fragments were then introduced into the suicide vector pCVD442 as follows. pSAB12 and pSAB19 were digested with *HindIII* and *EcoRI* and the DNA fragment

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containing either the *iryA* deletion (from pSAB12) or the *iryA* deletion-*slt-IB*-substitution (from pSAB19) were made blunt-ended by the Klenow fragment of DNA polymerase I. Following ligation to *SalI* linkers, the fragments were ligated into the unique *SalI* site of pCVD442, yielding plasmids pSAB14 and pSAB24 respectively, and propagated in the permissive strain SM10  $\lambda$  pir. Plasmid pCVD442 is a recently described suicide vector containing the pir-dependent R6K replicon, ampicillin resistance, and the *sacB* gene from *Bacillus subtilis* (Donnenberg et al., Infect. Immun. 59:4310-4317, 1991).

#### Construction of VAC1 and VAC2

*V. cholerae* strain SBC20 is an *iryA::TnpHoA* derivative of 0395-N1 (Pearson et al., Res. Microbiol. 141:893-899, 1990). The kanamycin resistance marker in *TnpHoA* allowed screening of mutants for deletion of *iryA* (and hence *TnpHoA*) by assessing susceptibility to kanamycin. The *iryA* allele of SBC20 was replaced with either the previously constructed *iryA* deletion, or the *iryA* deletion containing *slt-IB*, as follows. Plasmids pSAB14 and pSAB24 were electroporated into SBC20, with selection for ampicillin and streptomycin resistance. Doubly-resistant colonies contained the respective plasmids integrated into the chromosome by homologous recombination involving either the upstream or downstream fragments of *iryA* on pSAB14 or pSAB24, with creation of a merodiploid state. One such colony from the integration of pSAB14 into the chromosome of SBC20 was selected and named B014-1; one from the integration of pSAB24 into the chromosome of SBC20 was named B024-1. B014-1 and B024-1 were grown overnight in LB media without ampicillin selection, then plated on LB media with 10% sucrose but without NaCl, and grown at 30°C for 30 hours, thereby selecting for clones that had deleted the integrated *sacB* gene (Blomfield et al., Mol. Microbiol. 5: 1447-1457,

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1991). Sucrose-resistant colonies that are ampicillin susceptible but kanamycin resistant have re-excised the plasmid (yielding the parent SBC20, which contains the kanamycin resistance marker in *TnpA*); those that are both ampicillin and kanamycin susceptible have resolved the merodiploid state to replace the *iryA* locus in SBC20 with either the *iryA* deletion from pSAB14 or the *iryA* deletion-*slt-IB* fragment from pSAB24. Approximately 10% of sucrose-resistant colonies that were ampicillin-susceptible were also kanamycin-susceptible. One of these colonies which had replaced the *iryA::TnpA* locus with the *iryA* deletion was further purified and named VAC1; one which had replaced the *iryA::TnpA* locus with *iryA::iryP-slt-IB* was named VAC2. Confirmation of the proper constructions in VAC1 and VAC2 was obtained by Southern hybridization of restriction enzyme-digested chromosomal DNA that was probed with several different DNA fragments to verify the expected deletion in *iryA*, as well as the introduction of the *slt-IB* within the deleted *iryA* segment.

Preparation of outer-membrane proteins, whole cell proteins, and periplasmic extracts.

Enriched outer membrane proteins were prepared from strains following growth in low- and high-iron media as previously described (Goldberg, Infect. Immun. 58:55-60, 1990). Proteins were separated by electrophoresis on a sodium dodecyl sulfate/10% polyacrylamide (SDS-PAGE) gel and visualized by staining with Coomassie brilliant blue. Whole cell proteins and periplasmic extracts were prepared from exponentially growing cells as previously described (Hovde et al., Proc. Natl. Acad. Sci. USA 85:2568-2572, 1988).

Immunodetection of StxB production.

Whole cell proteins and periplasmic extracts were separated on a SDS-15% PAGE gel as described above, then

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transferred to a NitroBind Transfer Membrane (Micron Separations Inc., Westboro, MA) with a semidry blotting apparatus (Hoefer Scientific Instruments, San Francisco, CA). Immunoreactive proteins were visualized after sequential incubation with polyclonal rabbit anti-Shiga toxin antiserum and goat anti-rabbit IgG-conjugated alkaline phosphatase (Sigma Chemical Co., St. Louis, MO), followed by staining for phosphatase activity as described previously (Hovde, *supra*). The amount of StxB present in periplasmic extracts or culture supernatants was quantitated with an enzyme-linked immunosorbent assay (ELISA) developed for the detection of Shiga toxin and modified for detection of purified StxB (Donohue-Rolfe et al., J. Clin. Microbiol. 24:65-68, 1986; Calderwood et al., Infect. Immun. 58:2977-2982, 1990).

HeLa cell cytotoxicity.

The cytotoxicity of periplasmic extracts or culture supernatants for HeLa cells was assayed in a quantitative cytotoxicity assay by determining the extent of HeLa cell detachment from microtiter plates (Gentry et al., J. Clin. Microbiol. 12:361-366, 1980). HeLa cells were grown at 37°C in a 5% CO<sub>2</sub> atmosphere in McCoy 5a (modified) medium containing 10% fetal calf serum and 100 µg of penicillin and streptomycin per ml. Freshly trypsinized cells were suspended in 0.1 ml of growth medium and allowed to attach to the wells of microtiter plates overnight. Serial dilutions of samples were added and the plates were again incubated overnight. The cells were fixed and then stained with crystal violet in a 5% ethanol - 2% formaldehyde solution. Stained cell monolayers were dissolved in ethanol and the A<sub>555</sub> read with a microtiter plate colorimeter.

Evaluation of virulence of vaccine strains.

50% lethal dose (LD<sub>50</sub>) assays were performed by oral inoculation of 3- to 4-day old CD1 suckling mice

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with either the parent *V. cholerae* strain 0395, an *irgA* mutant strain MBC40 (Goldberg et al., Infect. Immun. 58:55-60, 1990), the *ctxA* mutant strain 0395-N1, or VAC2. Cholera strains were grown overnight in LB medium at 30°C, pelleted, and resuspended in 0.5M NaHCO<sub>3</sub> (pH 8.5). Mice were orally inoculated with serial dilutions of organisms, then kept at 30°C. Four or more mice were used per dose of bacteria. Survival was determined at 40 h (Taylor et al., Proc. Natl. Acad. Sci. USA 84:2833-2837, 1987).

## RESULTS

Confirmation of vaccine strain construction.

(i) Southern hybridization analysis. To confirm the construction of the vaccine strains, chromosomal DNA was purified from *V. cholerae* parent strains 0395-N1 and SBC20, the merodiploid strains B014-1 and B024-1, and the vaccine strains VAC1 and VAC2. The chromosomal DNAs were digested with *Hind*III, separated on agarose gels, and transferred to membranes for Southern hybridizations. The Southern hybridizations of these digests, probed with four different fragment probes, are shown in Fig. 2. The location of the fragment probes within the *irgA* gene is shown in Fig. 1. The presence and size of the recognized fragments is consistent with the constructions depicted in Fig. 1, confirming the deletion of *irgA* in VAC1 and the deletion-replacement of the *irgA* locus with *irgA::irgP-sltIB* in VAC2.

(ii) Outer membrane protein analysis. Outer membrane proteins were prepared from strain 0395-N1 grown in low- and high-iron media and from strains SBC20, VAC1 and VAC2 following growth in low-iron media, then separated by electrophoresis on a SDS-PAGE gel (Fig. 3). *IrgA*, the 77 kilodalton (kDa) major iron-regulated outer membrane protein (Goldberg et al., Infect. Immun. 58:55-60, 1990), is present in 0395-N1 grown in low iron but is

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absent in SBC20 (an *irgA* mutant) and the vaccine strains, confirming the deletion of *irgA* in VAC1 and VAC2.

Iron-regulated expression of the Shiga toxin B subunit in VAC2.

(i) Western blot analysis of StxB production in VAC2. Western blot analysis of whole cell proteins and periplasmic extracts of VAC2 grown in high- and low-iron media demonstrated the production of a 7.7 kDa protein recognized by polyclonal rabbit anti-Shiga toxin antiserum in both whole cell proteins and periplasmic extracts prepared from VAC2 grown in low-iron media; no such protein was recognized in proteins prepared from the vaccine strain grown in high-iron media, demonstrating that the production of StxB is tightly iron-regulated (data not shown).

(ii) Quantitation of StxB production from *irgP-slt-IB* in plasmid pSAB19 and VAC2. To verify iron-regulated production of StxB by *irgP-slt-IB* in plasmid pSAB19, and compare it with StxB production by VAC2, we first had to return pSAB19 to the *V. cholerae* background because *irgP* is not active in *E. coli* (Goldberg et al., Proc. Natl. Acad. Sci. USA 88:1125-1129, 1991). The production of StxB by strains 0395-N1(pSAB19) and VAC2 was quantitated using a sandwich ELISA, with a monoclonal antibody specific for StxB as the capture molecule. Purified StxB, in measured amounts, was used as the standard. As shown in Table 2, both 0395-N1(pSAB19) and VAC2 express StxB in a tightly iron-regulated fashion, as expected, and produce five times the amount of B subunit made by the reference strain, *Shigella dysenteriae* 60R, under low-iron conditions.

Virulence of vaccine strains.

(i) Cytotoxicity to HeLa cells. The cytotoxicity of periplasmic extracts or culture supernatants of strains 0395-N1(pSAB19) and VAC2, grown in low-iron

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media, was assayed as described (Gentry et al., J. Clin. Microbiol. 12:361-366, 1980), and compared to the *S. dysenteriae* strain 60R. Neither 0395-N1(pSAB19) or VAC2 had detectable cytotoxicity in periplasmic extracts or supernatants, in contrast to periplasmic extracts of *S. dysenteriae* 60R, which were cytotoxic to at least a  $10^5$ -fold dilution (data not shown).

(ii) LD<sub>50</sub> ASSAYS. The results of LD<sub>50</sub> assays for the wild-type *V. cholerae* strain 0395, ctxA mutant strain 0395-N1, *iryA* mutant strain MBG40, and vaccine strain VAC2 in the suckling mouse model are shown in Table 3. *V. cholerae* strain MBG40, an *iryA::TnpA* mutant of strain 0395, had an LD<sub>50</sub> in suckling mice that was 2 orders of magnitude higher than that for the parental strain 0395, as previously demonstrated (Goldberg et al., Infect. Immun. 58:55-60, 1990). Strain 0395-N1, deleted for the A subunit of cholera toxin, was avirulent at an inoculum of  $2 \times 10^8$  organisms in this model. The vaccine strain VAC2, despite expressing StxB at high level, remains avirulent in this model at an inoculum of  $2 \times 10^9$  organisms, similar to its parent strain 0395-N1.

#### USE

The *V. cholerae* strains of the invention are useful as bivalent vaccines capable of inducing immunity to *V. cholerae* and to an antigen derived from a second infectious organism. Because the strains are attenuated (i.e., do not induce a significant toxic reaction in the vaccinee), they can be used as live-cell vaccines, permitting effective immunity to result from administration of a single dose of the vaccine. An effective oral dose of the vaccine would contain approximately  $10^6$  to  $10^8$  bacteria in a volume of approximately 150 ml liquid. The diluent used would typically be water or an aqueous solution, such as

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2 grams of sodium bicarbonate dissolved in 150 ml distilled water, which may be ingested by the vaccinee at one sitting, either all at once or over any convenient period of time.

#### Other Embodiments

Other embodiments are within the claims set forth below. For example, the host bacterium (the bacterium the chromosome of which is engineered to encode a heterologous antigen) can be *E. coli* or any other enteric bacterium, including *Salmonella*, *Shigella*, *Yersenia*, *Citrobacter*, *Enterobacter*, *Klebsiella*, *Morganella*, *Proteus*, *Providencia*, *Serratia*, *Plesiomonas*, and *Aeromonas*, all of which are known or believed to have iron-regulated promoters similar to the Fur-binding promoters of *E. coli*, and which may have other iron-regulated promoters analogous to that of *iryA*. Also potentially useful would be a bacille Calmette-Guerin (BCG) vaccine strain engineered to encode a heterologous antigen linked to an iron-regulated promoter. The promoter used can be native to the species of the host bacterium, or can be a heterologous promoter (i.e., from a species other than that of the host bacterium) engineered into the host bacterium along with the heterologous antigen coding sequence, using standard genetic engineering techniques. Multiple heterologous antigen coding sequences linked to the same or different iron-regulated promoter sequences can be inserted into a given chromosome, using techniques analogous to those set forth above, to produce a multivalent vaccine strain.

Those who practice in the field of prokaryotic gene expression will realize that, while naturally-occurring promoter sequences are preferred, synthetic sequences such as a consensus Fur-binding sequence or a hybrid of two or more Fur-binding sequences would also be

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expected to be useful in the chromosomes of the invention. Alteration, addition or deletion of one or a few nucleotides within a naturally-occurring promoter sequence such as the *lrpA* promoter would generally not affect its usefulness. The invention therefore encompasses iron regulated promoters having such inconsequential changes.

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Table 1. Bacterial strains and plasmids used in this study

Strain or plasmid	Relevant genotype or phenotype	Ref. or source
<b><i>V. cholerae</i> strains</b>		
0395	<i>Sm<sup>r</sup></i>	1
0395-W1	0395 <i>ctxA</i> , <i>Sm<sup>r</sup></i>	1
SBC20	0395-W1 <i>lrpA::TnpA</i> , <i>Sm<sup>r</sup></i> , <i>Km<sup>r</sup></i>	2
MB640	0395 <i>lrpA::TnpA</i> , <i>Sm<sup>r</sup></i> , <i>Km<sup>r</sup></i>	3
10 B014-1	SBC20 with pSAB14 integrated into <i>lrpA</i> , <i>Sm<sup>r</sup></i> , <i>Km<sup>r</sup></i> , <i>Ap<sup>r</sup></i>	4
B024-1	SBC20 with pSAB24 integrated into <i>lrpA</i> , <i>Sm<sup>r</sup></i> , <i>Km<sup>r</sup></i> , <i>Ap<sup>r</sup></i>	4
VAC1	0395-W1 <i>ΔlrpA</i> , <i>Sm<sup>r</sup></i>	4
15 VAC2	0395-W1 <i>ΔlrpA::lrpP-elt-IB</i> , <i>Sm<sup>r</sup></i>	4
<b><i>E. coli</i> strains</b>		
SM10 $\lambda$ <i>pir</i>	<i>chi thr leu tonA lacY supE</i> <i>recA::RP4-2-Tc::Mu <math>\lambda</math> pir66K</i> , <i>Km<sup>r</sup></i>	5
<b>Plasmids</b>		
20 pRG59	pSAB22 with 4.7-kbp of <i>V. cholerae</i> MB640 chromosome, containing DNA upstream and at the 5' terminus of <i>lrpA</i> , as well as the <i>lrpA::TnpA</i> fusion joint from this strain.	6
25 pSAB25	3.0 kbp <i>SmaI</i> - <i>HluI</i> fragment of <i>V. cholerae</i> 0395 chromosome, containing DNA at the 3' terminus and downstream of <i>lrpA</i> , made blunt-ended at the <i>HluI</i> site and ligated into <i>SmaI</i> -digested pOC19.	4
30 pSBC52	pOC19 with a promoterless gene for the B subunit of <i>SLT-I</i> (identical to <i>StxB</i> ) cloned between the <i>EcoRI</i> and <i>HindIII</i> sites.	4
35 pCVD442	Suicide vector composed of the <i>mob</i> , <i>ori</i> , and <i>bla</i> regions from pCF704 and the <i>secB</i> gene of <i>Bacillus subtilis</i> .	7
40	<i>Ap<sup>r</sup></i> , ampicillin resistance; <i>Km<sup>r</sup></i> , kanamycin resistance; <i>Sm<sup>r</sup></i> , streptomycin resistance.	

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## Ref. or source:

1. Makalans et al., Nature 306:551-557, 1983.
2. Pearson et al., Res. Microbiol. 141:893-899, 1990.
3. Goldberg et al., Infect. Immun. 58:55-60, 1990.
- 5 4. This study.
5. Miller et al., J. Bacteriol. 170:2575-2583, 1988.
6. Goldberg et al., J. bacteriol. 172:6863-6870, 1990.
7. Donnenberg and Kaper, Infect. Immun. 59:4310-4317, 1991.

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Table 2. Production of Shiga toxin B subunit by various strains following growth in high- and-low iron conditions

	Strain	Periplasmic extract <sup>a</sup>		Supernatant <sup>a</sup>	
		High-iron	Low-iron	High-iron	Low-iron
5	Iron				
	0395-W1	— <sup>b</sup>	—	—	—
	0395-W1 (pSAB19)	15.5	3,620	0.16	3.5
10	VAC2	0.87	4,130	—	0.73
	<i>S.dysenteriae</i> 60R	238	674	0.8	16.4

<sup>a</sup> ng/50 OD<sub>600</sub> of original culture<sup>b</sup> < 0.1 ng

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Table 3. Virulence assays of wild-type and mutant strains of *Vibrio cholerae* in suckling mice

	Strain	LD <sub>50</sub> (no. of bacteria)
5	0395	$1 \times 10^5$
	MBG40	$1 \times 10^7$
	0395-W1	$> 2 \times 10^9$
10	VAC2	$> 2 \times 10^9$

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SEQUENCE LISTING

## (1) GENERAL INFORMATION:

- (i) APPLICANT: Calderwood, Stephen B.  
Butterton, Joan M.  
Nekelanos, John J.
- (ii) TITLE OF INVENTION: HETEROLOGOUS ANTIGENS IN LIVE CELL VACCINE STRAINS
- (iii) NUMBER OF SEQUENCES: 12
- (iv) CORRESPONDENCE ADDRESS:
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(B) STREET: 225 Franklin Street  
(C) CITY: Boston  
(D) STATE: Massachusetts  
(E) COUNTRY: U.S.A.  
(F) ZIP: 02110-2804
- (v) COMPUTER READABLE FORM:
- (A) MEDIUM TYPE: 3.5" Diskette, 1.44 Mb  
(B) COMPUTER: IBM PS/2 Model 50X or 556X  
(C) OPERATING SYSTEM: MS-DOS (Version 5.0)  
(D) SOFTWARE: WordPerfect (Version 5.1)
- (vi) CURRENT APPLICATION DATA:
- (A) APPLICATION NUMBER: 08/020,501  
(B) FILING DATE: February 22, 1993  
(C) CLASSIFICATION:
- (vii) PRIOR APPLICATION DATA:
- (A) APPLICATION NUMBER:  
(B) FILING DATE:
- (viii) ATTORNEY/AGENT INFORMATION:
- (A) NAME: Clark, Paul T.  
(B) REGISTRATION NUMBER: 30,162  
(C) REFERENCE/DOCKET NUMBER: 00786/136001
- (ix) TELECOMMUNICATION INFORMATION:
- (A) TELEPHONE: (617) 542-5070  
(B) TELEFAX: (617) 542-8906  
(C) TELE: 200154

## (2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 1:

## (i) SEQUENCE CHARACTERISTICS:

- (A) LENGTH: 1535  
(B) TYPE: nucleic acid  
(C) STRANDEDNESS: both  
(D) TOPOLOGY: linear

## (ii) SEQUENCE DESCRIPTION: SEQ ID NO: 1:

- 27 -

ATCGATGATA AAAAATCCCG CTGCGGCGGG ATTTTATTAT GCCACTCATC GGGCCTTGCT 60  
 TCGCGGAGCG CATCAATAAA TAGCGCCAGC CGAAGTGGGT GACGACCGAG CGGATGAGAG 120  
 CAOTTGATTT CTGTTGGCTG TGATTGCCAT CCGTTGAGCG AAGGAATGAG GCTGCGGCGA 180  
 TCGCGGCTTT GAAAGCCATT GCGAAGCCAA GTGGGAGCCA AACCAATACC ACGAGCTTTA 240  
 GCAATGUCAT GCGCTTGCAT GCGAGATTA TCGCTTTGTA AAGGACTCTC TACTGCTGGC 300  
 AGTGAATAAC TCGGAACTCT TCGATGCTGC AGTTCAAGCT CCGCGCGCGG ACAAGCAATA 360  
 AAATCAATCC ATGCGTGAAT AATCAGCTCA CGAGGATGGG TCGGTTTATC TCGATGCGGC 420  
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 CCGATGCGGG GCGCGTCTTC AATCCAAATC ATCAATCGG GCTCAAGCAC CTCATCACTG 540  
 TTTGAAACT GCGTGAATAG ACGGATCTTC AATGTGGAAT GCTGCTGCAT AAATCATCC 600  
 AATACTTGGC TGAGCCAGCG GCGATCAAA TTGGGCTGTA CCACGAGCT GAGTTGCGCA 660  
 GTCACTTGAAT TTTCAATTC TTGCAAGCT TCGTACTTT TATTGCGCAG TTCAAGTAT 720  
 TGCTCGAGT AAACCGCAAA CACTTCTCT GCTTTGGTGA GCGTTAAGCG GTTGGCTTGA 780  
 CGCATCAACA AGCTTTGTC CAGTCTCTCT TCAAGTTGCG CCAAGCGCG AACTCAGGCTG 840  
 GATTTAGGCT GTTCAAGCGC TTGCGCAGCG GCAATCAGCG TTTATGTTG GCAAGCGCA 900  
 TCGAAGCTT TTAAGCGCT GAGATCTTC ATAGGTATT GACCGTTAAA GAATAATTAC 960  
 CACAGAGCTT CCATATTTGG ACGCAACTAT TCGATGCTC GATCTATCT CACTACAGAA 1020  
 TATATGAATA ATCGCTTCT GAAATTAAGA ATATTTATCA TTTAAGGAG TGTTAA 1076  
 ATG TCC AGA TTC AAT CCA TCC CCC GTC AGT TTA TCT GTG ACA CTA GGC 1124  
 Met Ser Arg Phe Asn Pro Ser Pro Val Ser Leu Ser Val Thr Leu Gly  
 1 5 10 15  
 TTA ATG TTT TCG GCT ACC GCT TTT GCT CAA GAC CGG ACG AAA ACG GAT 1172  
 Leu Met Phe Ser Ala Ser Ala Phe Ala Gln Asp Ala Thr Lys Thr Asp  
 20 25 30  
 GAA ACC ATG GTG GTC ACT CGG CGG GGA TAC CGC CAA GTC ATT CAA AAT 1220  
 Glu Thr Met Val Val Thr Ala Ala Gly Tyr Ala Gln Val Ile Gln Asn  
 35 40 45  
 CCA CCA GCG AGT ATC AGT GTG ATT TCA AGA GAA GAT CTG GAA TCT CGC 1268  
 Ala Pro Ala Ser Ile Ser Val Ile Ser Arg Glu Asp Leu Glu Ser Arg  
 50 55 60  
 TAT TAC GGT GAT GTG ACC GAT CGG CTA AAA ACC GTA CGG GGT GTG ACA 1316  
 Tyr Tyr Arg Asp Val Thr Asp Ala Leu Lys Ser Val Pro Gly Val Thr  
 65 70 75 80  
 GTC ACC GGA GGG GGC GAT ACT ACC GAT ATC ACC ATT CGT GGT ATG GCA 1364  
 Val Thr Gly Gly Gly Asp Thr Thr Asp Ile Ser Ile Arg Gly Met Gly  
 85 90 95  
 TCA AAC TAT ACT CTT ATC TTG GTG GAT GGT AAG CGC CAA ACC TCA CGC 1412  
 Ser Asn Tyr Thr Leu Ile Leu Val Asp Gly Lys Arg Gln Thr Ser Arg  
 100 105 110

- 28 -

CAG ACC GGT CCA AAC AGC GAT CGC CGG GGC ATT GAG CAA GCT TCG TTA 1460  
 Gln Thr Arg Pro Asn Ser Asp Gly Pro Gly Ile Glu Gln Gly Trp Leu  
 115 120 125  
 CGG CCA CTG CAA CGG ATT GAA GGT ATC GAG GTG ATC GGT CGC CGG ATG 1508  
 Pro Pro Leu Gln Ala Ile Glu Arg Ile Glu Val Ile Arg Gly Pro Met  
 130 135 140  
 TCT ACC CTG TAC GGC TCG GAT GCT GAC 1535  
 Ser Thr Leu Tyr Gly Ser Asp Ala Asp  
 145 150

(2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 2:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 51  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

(11) SEQUENCE DESCRIPTION: SEQ ID NO: 2:

TCCATGTGTC GATCTATCTC CACTACAGAA TATATGAATA ATCGGCTTCT G 51

(2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 3:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 120  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

(11) SEQUENCE DESCRIPTION: SEQ ID NO: 3:

AGATCTTCCA TAGGTATTTC ACCGTTAAG AATAATTACC ACAGAGCTTC CATATTGCA 60  
 CCGAAGTATT CCATGTGTCG ATCTATCTCC AGTACAGAA ATATGAATAA TCGGCTTCTG 120

(2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 4:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 158  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

(11) SEQUENCE DESCRIPTION: SEQ ID NO: 4:

AGATCTTCCA TAGGTATTTC ACCGTTAAG AATAATTACC ACAGAGCTTC CATATTGCA 60  
 CCGAAGTATT CCATGTGTCG ATCTATCTCC AGTACAGAA ATATGAATAA TCGGCTTCTG 120  
 AATTAAGAA TAATTATCAT TTAAGGCACT GATAAATG 158

- 29 -

## (2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 5:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 80  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

## (11) SEQUENCE DESCRIPTION: SEQ ID NO: 5:

CGATCTATCT CCACTACAGA ATATATGAAT AATCCGCTTC TGAATTAAG AATAATTATC 60  
 ATTAAAGCA GTGTAAGAT 80

## (2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 6:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 137  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

## (11) SEQUENCE DESCRIPTION: SEQ ID NO: 6:

AAGCTTTTAC GCGGCTGAGA TCTTGACATG GTATTGACC CTTAAGAAT AATTACCACA 60  
 GAOTTCAT ATTGACCG AACTATCCA TGTGCGATC TATCTCCAGT ACAGAATATA 120  
 TGAATAATCC GCTTCTGAAA 137

## (2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 7:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 175  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

## (11) SEQUENCE DESCRIPTION: SEQ ID NO: 7:

AAGCTTTTAC GCGGCTGAGA TCTTGACATG GTATTGACC CTTAAGAAT AATTACCACA 60  
 GAOTTCAT ATTGACCG AACTATCCA TGTGCGATC TATCTCCAGT ACAGAATATA 120  
 TGAATAATCC GCTTCTGAAA TTAAGAATAA TATCATTTA AAGGAGTGT AAATG 175

## (2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 8:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 534  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

- 30 -

## (11) SEQUENCE DESCRIPTION: SEQ ID NO: 8:

AAGCTTTTAC GCGGCTGAGA TCTTGACATG GTATTGACC CTTAAGAAT AATTACCACA 60  
 GAOTTCAT ATTGACCG AACTATCCA TGTGCGATC TATCTCCAGT ACAGAATATA 120  
 TGAATAATCC GCTTCTGAAA TTAAGAATAA TATCATTTA AAGGAGTGT AAATG 180  
 ATTCAATCCA TCCCGGCTCA GTTATCTGT GACACTAGCC TTAATGTTT CCGGTAGCGC 240  
 TTTGCTCAA GACCGGACGA AAAGCGATGA AACCATGCTG GTACTGCGG CCGGATACGC 300  
 CGAAGTGATT CAATATGCGC CAGCCATAT CAOTGTGATT TCAAGGAGG ATCTGGAATC 360  
 TCGCTATTAC CGTATGTCGA CGATGCGCT AAAAAGCGTA CCGGCTGCA CACTCACCGG 420  
 ACGGGGCGAT ACTACGATA TCAGCATTCG TCGTATGCGA TCAAACTATA CTCTTATCTT 480  
 GGTGATGCT AAGCGCCAAA CTTCAAGCCA GACCGGTCCA AACAGGATG GGGC 534

## (2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 9:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 517  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

## (11) SEQUENCE DESCRIPTION: SEQ ID NO: 9:

AGATCTTCCA TAGGTATTG ACCCTTAAG AATAATTACC ACAGACCTTC CATATTGGA 60  
 CGAACTATT CCATGTCTCG ATCTATCTCC ACTACAGAAT ATATGAATAA TCGCTTCTG 120  
 AATTAGAA TAATTATCAT TTAAGGAGT GGTAAATGTC CAGATTCAAT CCATCCCGCG 180  
 TCAGTTATC TGTGACACTA CGCTTAATCT TTTCGGCTAG CGCTTTTCT CAAGACCGCA 240  
 CGAAACCGA TGAACCATG GTGTCTACTG CCGCGCGATA CGCGCAAGTG ATTCAAAATG 300  
 CACCAACCGG TATCATGCTG ATTTCAAGAG AAGATCTGCA ATCTGCTAT TACCGTGATG 360  
 TGACCGATCG GCTAAAGGC GTACCGGCTG TGACACTGC CGAGCGCGGC GATACTACCG 420  
 ATATCAGCAT TGTGTGATG GGATCAAACT ATACTCTTAT CTGTGCGAT GGTAAAGCGC 480  
 AAACCTCAG CCAAGCCCTT CCAAGACGGG ATGCGCC 517

## (2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 10:

## (1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 439  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: both  
 (D) TOPOLOGY: linear

## (11) SEQUENCE DESCRIPTION: SEQ ID NO: 10:

- 31 -

CGATCTATCT CCAGTACAGA ATATATGAAT AATCGCTTC TGAATTAG AATAATTATC 60  
 ATTAAAGGA GTGCTAAA<sup>2</sup>G TCCAGATTCA ATCCATCCCC CUTCAGTTTA TCTGTGACAC 120  
 TAGGCTTAAT GTTTTGGCT AGCGCTTTT CTCAGAGCCG GACGAAACG GATGAAACCA 180  
 TCGTGTGAC TCGGGGGGA TACCGCCAG TGATTCAAA TCCACCCGCC AGTATCAGTG 240  
 TGATTCAAG AGAGATCTG GAATGTGCT ATTACCTGA TGTGACCGAT GCGCTAAGAA 300  
 GCGTACCGGG TGTGACATC ACCGGAGGG GCGATACAC CGATATCAGC ATTCTGTGTA 360  
 TCGGATCAA CTATACTCTT ATCTTGTGG ATGCTAAGCG CCAAACTCA GCGCAGAGCC 420  
 GTCCAAACAG CGATGCCC 439

(2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 11:

(1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 42  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: single  
 (D) TOPOLOGY: linear

(11) SEQUENCE DESCRIPTION: SEQ ID NO: 11:

CGAATCTC TAGAGATATC GTTGGAAAT GTGAGCGAT AA 42

(2) INFORMATION FOR SEQUENCE IDENTIFICATION NUMBER: 12:

(1) SEQUENCE CHARACTERISTICS:

(A) LENGTH: 45  
 (B) TYPE: nucleic acid  
 (C) STRANDEDNESS: single  
 (D) TOPOLOGY: linear

(12) SEQUENCE DESCRIPTION: SEQ ID NO: 12:

CCAGCTTCT CGACCCCGGG ATTAAACAT TATGAATCT CCGCT 45

- 32 -

## CLAIMS

1. A bacterial chromosome containing a DNA sequence encoding a heterologous antigen, said DNA sequence being functionally linked to an iron-regulated promoter.
2. The chromosome of claim 1, wherein said chromosome is a *Vibrio cholerae* chromosome.
3. The chromosome of claim 1, wherein said chromosome is a chromosome of an *E. coli* bacterium, a *Shigella* bacterium, a *Salmonella* bacterium, a *Yersenia* bacterium, a *Citrobacter* bacterium, an *Enterobacter* bacterium, a *Klebsiella* bacterium, a *Proteus* bacterium, a *Providencia* bacterium, a *Serratia* bacterium, a *Vibrio* bacterium, a *Plesiomonas* bacterium, an *Aeromonas* bacterium, or a bacille Calmette-Guerin (BCG).
4. The chromosome of claim 1, wherein said promoter is the promoter of a naturally-occurring *V. cholerae* gene.
5. The chromosome of claim 4, wherein said promoter is the *V. cholerae* *irgA* promoter, and said chromosome lacks part or all of the *irgA* coding sequence.
6. The chromosome of claim 5, wherein said promoter comprises a nucleotide sequence substantially identical to SEQ ID NO: 2.
7. The chromosome of claim 1, wherein said heterologous antigen is a nontoxic polypeptide which induces an antigenic response in an animal.

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8. The chromosome of claim 7, wherein said polypeptide is a portion or all of a protein naturally expressed by an infectious organism.
9. The chromosome of claim 8, wherein said  
5 infectious organism is a bacterium.
10. The chromosome of claim 9, wherein said polypeptide is an immunogenic, nontoxic subunit or fragment of a bacterial toxin.
11. The chromosome of claim 10, wherein said  
10 toxin is Shiga toxin, diphtheria toxin, *Pseudomonas* exotoxin A, cholera toxin, pertussis toxin, tetanus toxin, anthrax toxin, *E. coli* heat-labile toxin (LT), *E. coli* heat-stable toxin (ST), or *E. coli* Shiga-like toxin.
12. The chromosome of claim 9, wherein said  
15 protein is an OSP (Outer Surface Protein) of *Borrelia burgdorferi*.
13. The chromosome of claim 8, wherein said infectious organism is a virus and said polypeptide is an immunogenic portion of a viral capsid.
- 20 14. The chromosome of claim 13, wherein said virus is a human immunodeficiency virus (HIV), one of the Herpes viruses, an influenza virus, a poliomyelitis virus, a measles virus, a mumps virus, or a rubella virus.
- 25 15. The chromosome of claim 8, wherein said infectious organism is a eukaryotic parasite.

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16. The chromosome of claim 15, wherein said  
parasite is the causative agent for malaria, pneumocystis pneumonia, or toxoplasmosis.
17. The chromosome of claim 16, wherein said  
5 protein is a malarial circumsporozoite protein.
18. The chromosome of claim 2, wherein said  
chromosome does not encode biologically active cholera toxin A subunit.
19. The chromosome of claim 5, wherein said  
10 chromosome does not encode biologically active cholera toxin A subunit.
20. A *V. cholerae* chromosome containing a DNA  
sequence encoding a heterologous antigen, said DNA  
sequence being functionally linked to a naturally-  
15 occurring *V. cholerae* promoter.
21. The chromosome of claim 20, wherein said  
promoter is the promoter of a naturally-occurring gene  
encoding a *V. cholerae* virulence factor that is  
nonessential for growth of said cell, the coding sequence  
20 encoding said virulence factor being mutated or deleted  
so that said chromosome cannot express a biologically  
active form of said virulence factor.
22. The chromosome of claim 20, wherein said  
promoter is the *irpA* promoter.
- 25 23. The chromosome of claim 20, wherein said  
heterologous antigen is part or all of a nontoxic  
polypeptide which is naturally expressed by an infectious

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organism, which antigen induces an antigenic response in an animal.

24. The chromosome of claim 23, wherein said infectious organism is a bacterium.

25. The chromosome of claim 24, wherein said antigen is an immunogenic, nontoxic subunit or fragment of a bacterial toxin.

26. The chromosome of claim 25, wherein said toxin is Shiga toxin, diphtheria toxin, *Pseudomonas* exotoxin A, cholera toxin, pertussis toxin, tetanus toxin, anthrax toxin, *E. coli* LT, *E. coli* ST, or *E. coli* Shiga-like toxin.

27. The chromosome of claim 23, wherein said infectious organism is a virus and said antigen is an immunogenic portion of a viral capsid.

28. The chromosome of claim 27, wherein said virus is a human immunodeficiency virus (HIV), one of the Herpes viruses, an influenza virus, a poliomyelitis virus, a measles virus, a mumps virus, or a rubella virus.

29. The chromosome of claim 23, wherein said infectious organism is a eukaryotic parasite.

30. The chromosome of claim 29, wherein said parasite is the causative agent for malaria, pneumocystis pneumonia, or toxoplasmosis.

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31. The chromosome of claim 20, wherein said chromosome does not encode biologically active cholera toxin A subunit.

32. A *V. cholerae* cell, the chromosome of which is the chromosome of claim 1.

33. A *V. cholerae* strain, the chromosome of which is the chromosome of claim 1.

34. A homogeneous population of *V. cholerae* cells, each of which comprises the chromosome of claim 1.

35. A live-cell vaccine comprising the cell of claim 32 in a pharmaceutically acceptable diluent suitable for oral administration.

36. The vaccine of claim 35, wherein said chromosome does not encode biologically active cholera toxin A subunit.

37. The vaccine of claim 36, wherein said chromosome does not encode biologically active IrqA.

38. The vaccine of claim 37, wherein said heterologous antigen is Shiga-like toxin B subunit.

39. A method of vaccinating an animal comprising orally administering to said animal the vaccine of claim 35.

40. The method of claim 39, wherein said animal is a human.

FIG. 1

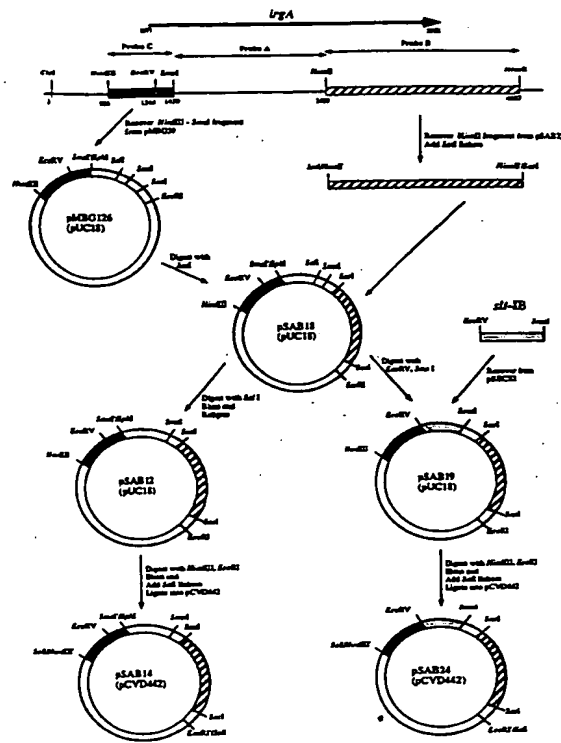


Fig. 2A

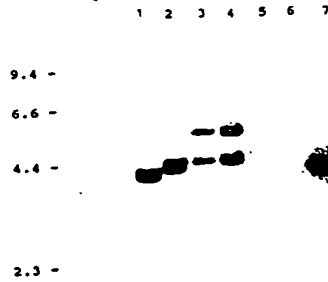
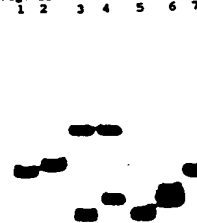
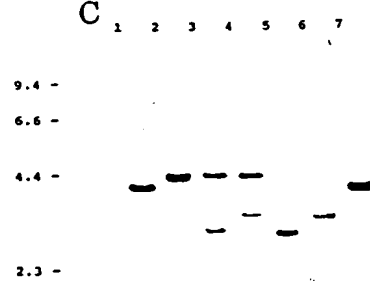


Fig. 2B



C



D



## INTERNATIONAL SEARCH REPORT

International application No.  
P. 7/US94/01780

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	INFECTION AND IMMUNITY, Volume 58, No.1, issued January 1990, Goldberg et. al., "Identification of an iron-regulated virulence determinant in <i>Vibrio cholerae</i> , using <i>Typhoid</i> mutants, pages 55-60, see entire document.	1-40
Y	NATURE, Volume 327, issued 11 JUNE 1987, Jacobs et al., "Introduction of foreign DNA into mycobacteria using a shuttle plasmid", pages 532-534, see entire document.	1-40

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